

The Lead Tungstate Electromagnetic Calorimeter of CMS

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Abstract. The design of the CMS Electromagnetic Calorimeter, the calibration strategy and the performance of final components in beam tests are described.

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The Compact Muon Solenoid (CMS) detector [1] is a general purpose detector to be installed at the LHC at CERN. The discovery of the Higgs boson is a primary goal and $H \rightarrow \gamma\gamma$ is the most promising discovery channel if the mass is between 114 and 130 GeV. In this mass range the width is very narrow, but the signal will lie above an irreducible background and so good energy resolution is crucial. The Electromagnetic Calorimeter (ECAL) [2] of CMS is a hermetic homogeneous calorimeter with 61,200 lead tungstate (PbWO_4) crystals in the barrel part, closed by 7,324 crystals in each of two end-caps. It will be mounted inside a 4 Tesla superconducting solenoid.

The operating conditions require that the ECAL be fast, highly granular and have triggering ability, and be able to withstand radiation doses over 10 years of up to 4 kGy and $2 \cdot 10^{13} \text{ n/cm}^2$ in the barrel and 50 times more in the end-caps. In addition, the ECAL detector is nearly unserviceable, so that very reliable components are required.

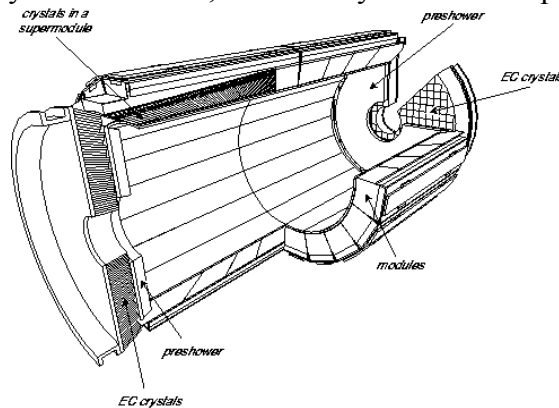


FIGURE 1. The CMS ECAL. It is 7.9 m long with a diameter of 3.6 m and weighs 90 tonnes.

The layout of the ECAL is shown in Fig. 1. In the barrel 400 or 500 crystals, held in alveolae made of 0.1 mm thick glass-fibre epoxy, are mounted in a module. Four

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modules are mounted in a supermodule of which there are 36 in the ECAL. In the end-caps 25 crystals are mounted in carbon fibre “supercrystals”, which are then assembled in half-dees, two of which form one end-cap. Pre-shower detectors made of lead and silicon strip detectors in front of the end-caps enhance γ/π^0 discrimination.

Lead tungstate has high density (8.28 g/cm^3) and a short radiation length (8.8 mm) allowing a compact design, while its small Moliere radius (2.19 cm) allows high granularity. Light emission peaks at 430 nm with 80% emitted within 25 ns. However, the light yield is only 5% of BGO’s and has a temperature dependence of $-2\%/^{\circ}\text{C}$. The radiation at the LHC will cause colour centre formation affecting the light transmission, making constant monitoring of the output necessary. The crystals are produced in Bogoroditsk and also in Shanghai, and after delivery their dimensions, light yield and transmission, and longitudinal uniformity and radiation resistance are checked. They have dimensions about $24 \times 24 \times 230 \text{ mm}^3$ in the barrel and $30 \times 30 \times 220 \text{ mm}^3$ in the end-caps, tapered and projecting 3° away from the interaction point. The choice of PbWO_4 has led to a compact high resolution calorimeter.

The photo-detectors must operate in the 4 T field and have gain because of the low light output of PbWO_4 , and be 99.9% reliable over 10 years. The avalanche photo-diodes (APDs) [3] in the barrel were specially developed by Hamamatsu Photonics for CMS. They are $5 \times 5 \text{ mm}^2$ in area, with 75% quantum efficiency and an excess noise factor of 2.1 at the operating gain of 50. They are insensitive to shower leakage particles traversing them. Their characteristics do not change after 10 years equivalent at 80°C , nor after 10 years LHC equivalent hadron irradiation except for an increased dark current. To ensure reliability, all APDs were screened with cobalt irradiation followed by four weeks at 80°C , and tested to gain 300. The vacuum photo-triodes [4] in the end-caps were specially developed by RIE, St Petersburg. They are 280 mm^2 in area, with 20% quantum efficiency and a radiation hard UV glass window. They can operate in the solenoid’s axial field; all are tested at 1.8 T, with 10% at 4 T.

The on-detector electronics [5] is custom designed in IBM $0.25 \mu\text{m}$ technology. The photodetector signal passes through a 50 ns shaping preamplifier and in parallel through amplifiers with gains of 1, 5 and 12 into 12-bit ADCs to provide a dynamic range of 20,000. The largest unsaturated ADC value is selected. Trigger primitives are generated from the digitised signals in groups of 25 channels, and sent to the upper

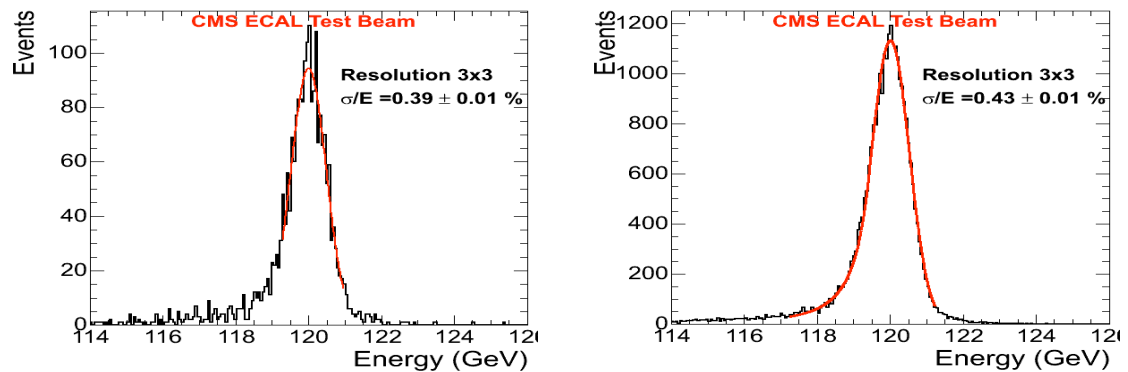


FIGURE 2. The energy resolution for 120 GeV electrons measured in a 3x3 matrix of crystals. Left: with the beam incident within 2 mm of the position of maximum response of the central crystal. Right: with the incident beam distributed over $20 \times 20 \text{ mm}$ of the crystal front face.

level read-out. Upon receipt of a trigger with 3 μ s latency, the data of each channel are sent to the upper level electronics. The communication with the upper level read-out is over 800 Mb/sec optical links. With the final system, the noise per channel was measured in 2004 to be 40 MeV rms, with negligible correlated noise, and an intrinsic energy resolution for 120 GeV electrons of 0.39 ± 0.01 %, shown in Fig. 2 (left), where the incident beam position was restricted. With a less restricted beam, so that the relative calibration of the 9 crystals used to reconstruct the energy are significant, as well as variations in the corrections for the losses in the gaps between the crystals, a resolution of 0.43 ± 0.01 % was achieved. This matches the ECAL design goal.

Because there is no beam at CERN in 2005, few supermodules will be calibrated with high energy electrons before installation. However, by using the crystals' measured light yield and the known variations in gain of the read-out, the channel-to-channel response variation can be reduced from 8% to 4% rms [6]. Further, cosmic rays will be used to intercalibrate the channels to 2-3% in a week [7,8]; the crystals surrounding that to be calibrated are used as veto counters to ensure that the muon transverses the crystal longitudinally, while the APD gains are raised to 200 to be almost free of the electronics noise. When the LHC is running, the energy deposit in jet events [9], Z mass reconstruction from its decay to e^+e^- , and momentum/energy comparison of isolated electrons from W decay will be used to successively intercalibrate and calibrate the ECAL to a precision of 0.5%.

At the LHC the light output of each crystal will fall and rise by around 5%, depending on the beam intensity, due to the formation and annealing of colour centres. This will be monitored with a system injecting laser light into the crystals. Beam tests have shown that this tracks the changes in light output to the necessary precision [10].

The CMS ECAL is compact, precise, fast, highly granular and radiation tolerant. Major components were specially developed and some new technologies (PbWO_4 , APDs) are now used in other detectors. Beam tests show that the design goals should be met, and that the discovery of the Higgs via its two-photon decay will be possible in 2-3 years of low luminosity running. The schedule for completing the ECAL is demanding but it is expected to be fully installed in time for the first LHC physics run.

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